

ISPM X-Band Uplink Technology Demonstration

Part I. Overview

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This is the first of a series of articles on the X-band uplink system development. The ground and spacecraft hardware research, design and implementation will lead to an end-to-end in-flight technology demonstration on the International Solar Polar Mission spacecraft. This article gives an introduction to the overall effort and establishes the flight experiment objectives. The expected improvements in the telecommunications performance are summarized. Also presented is a conceptual mission operations plan. Subsequent articles will address the system design and performance, report on the implementation progress, and finally evaluate the flight experiment results.

I. Introduction

The X-band uplink technology demonstration was established by agreements among the NASA Offices for Space Science (OSS), Aeronautics and Space Technology (OAST), and Space Tracking and Data Systems (OSTDS). The agreement, documented by a Memorandum of Understanding in October 1980, provides for the support of a flight technology demonstration experiment on the International Solar Polar Mission (ISPM) spacecraft to be launched in 1985 (Ref. 1).

The engineering experiment will culminate the X-band uplink development phase with an end-to-end demonstration of new ground and spacecraft technology and an assessment of benefits for future deep space missions — in particular, possible future gravitational wave investigations (Ref. 2) and the proposed Starprobe mission.

The benefits of an X-band uplink over an S-band uplink are several. For one, it is possible to obtain a greater signal power density at the spacecraft receiver for a given ground transmitter power and given size of ground antenna. An equally important advantage is that the phase and group velocities of an X-band signal are less perturbed by charged particles in the signal path through the ionosphere, interplanetary space and especially near the sun. Finally, the bandwidth allocations at X-band are wider and in a spectral region less crowded than S-band and less exposed to radio frequency interference (RFI) at this time.

To assure proper coordination of all segments of the X-band uplink development, the JPL Telecommunications Science and Engineering Division formed a task and a design team under the programmatic leadership of the Telecommu-

nications and Data Acquisition Office (TDA). The design team represents all major implementation areas and interfaces with the ISPM project, TRW (the ISPM spacecraft system contractor), and possible future users in the radio science community. The ground and spacecraft hardware developments have been proceeding (Refs. 3-6).

II. Scope and Responsibilities for the Flight Engineering Experiment

A. Scope

The scope of the X-band uplink development and demonstration conforms to the following key guidelines:

- (1) The flight experiment will be a technology demonstration only. Operational X-band uplink use for spacecraft mission enhancement or science investigations would require additional implementation.
- (2) X-band uplink capability will be implemented only at the R&D Deep Space Station (DSS 13), and therefore the ISPM X-band uplink sequences will be supported from that station.

Also implied in the ISPM Project's acceptance of the X-band uplink experiment is that the inclusion of the X-band receive capability will not jeopardize spacecraft reliability, nor will it impair baseline operational functions, such as S-band uplink commanding or X-band telemetry. Furthermore, mission operations impact shall be minimized. For these reasons, the on-board X-band uplink hardware will be inserted in only one of the redundant S-band uplink paths and in only one of the X-band downlink paths. Also, the X- to S-band downconverter and the X-diplexer can be bypassed by direct or stored command when not in use, leaving only the incremental losses due to an added transfer switch and cabling in the X-band downlink path. Figure 1 shows the ground and Spacecraft Telecommunications System and Fig. 2 shows the spacecraft Radio Frequency Subsystem in some detail.

Similarly, an X-band uplink systems liaison has been established with the ISPM Mission Operations System (MOS) to integrate the X-band uplink requirements and mission sequences into the ISPM mission operations plan.

B. Flight Hardware Responsibilities

JPL has the overall responsibility for the X-band uplink engineering experiment. The X-band uplink status is similar to that of the science experiments where the system contractor performs spacecraft integration of instruments furnished by the investigators. For the X-band uplink, TRW will integrate the hardware furnished by JPL. This is in contrast to all other spacecraft operational functions, including the S-band uplink

and X-band downlink, which are the responsibility of the system contractor.

The JPL X-band uplink task will supply to TRW one flight-model X- to S-band downconverter and one flight model X-band diplexer for integration aboard the NASA spacecraft. Consistent with its integration responsibility, TRW will specify and procure those components which lie in ISPM operational signal paths when the X-band uplink function is switched out. From Fig. 2 one can identify these components to be the coupler in the S-band uplink transponder Number 2 path and the transfer switch in the X-band downlink path from traveling-wave tube amplifier (TWTA) Number 1.

TRW will maintain the mass and power budget entries associated with the X-band implementation, and will also measure the circuit losses for the affected baseline ISPM links with the X-band uplink hardware passively switched in or out of the signal paths. TRW will account for these incremental losses in Design Control Tables for the baseline functions.

The JPL X-band uplink task will be responsible for all analysis, performance predictions and testing involving the X-band uplink. The pertinent links include commanding via X-band plus X-X and X-S doppler, ranging and coherent telemetry.¹ The task will also provide the liaison necessary to ensure that X-band uplink requirements become part of the ISPM Mission Plan, operational sequences, and DSN support plans.

C. Ground Hardware Responsibilities

The focal point of the X-band uplink ground development has been the design and implementation of modified DSS 13 subsystems under the TDA Advanced Development program. The ground development is being integrated with the spacecraft portions by system engineering provided by the X-band uplink design team under the same TDA program.

The DSS 13 development was divided into four main areas: a 20-kW X-band transmitter and controller, a dual X-S antenna feed horn and X-band diplexer to be housed in a modified 26-meter antenna feed cone, a high-stability X-band exciter-doppler extractor using a hydrogen maser timing reference, and a Block III receiver upgrade. Temperature control will be employed throughout for critical components.

The high-power transmitter and the phase stable 7145-7235 MHz exciter-doppler extractor are being developed (Refs. 3 and 4) and will be compatible with a companion goal of

¹A coherent X-uplink and X-downlink is abbreviated as X-X. Similarly, X-S means a coherent X-uplink and S-downlink.

achieving unattended operations. The stable reference depends upon hydrogen maser research and implementation (Ref. 5). The antenna feed design, development and testing has been proceeding, and it is planned for installation at DSS 13 in the fall of 1981 (Ref. 6).

In addition to the new station hardware under development, the X-band demonstration will require other ground equipment to be available at DSS 13 for the prelaunch and in-flight tests. Not all the planning has been completed at this time, and it will be necessary to coordinate with all other scheduled DSN activities. For example, a state-of-the-art hydrogen maser must be present during the crucial test and flight phases of the X-band demonstration. Likewise, all the data processing equipment needed for command modulation, telemetry acquisition and ranging measurements must be assured. The MU-2 ranging machine is desirable because of its dual-frequency capability, but its availability is subject at important times to high-priority users, such as Voyager at Uranus encounter.

The command and telemetry processing equipment may be shared between DSS 13 and the DSN Compatibility Test Areas located in JPL (CTA-21) and in the Merrit Island Launch Area (MIL-71). The equipment would reside at DSS 13 when needed by X-band uplink and would be transported to MIL-71 to support DSN launch commitments. However, this plan may be a problem depending on how the total mission set develops.

In the case of telemetry, another alternative may be to relay the demodulated subcarrier data from DSS 13 to DSS 12 via a microwave link for final processing as shown in Fig. 3, if the MIL-71 equipment were not available. The schedule for the support equipment, as well as the X-band uplink ground and space hardware, is given in Fig. 4. Resolution of the above issues will be part of the ongoing design team activity.

III. Flight Engineering Experiment Objectives

The X-band uplink flight experiment will test the capabilities of all the pertinent telecom functions under the varied conditions applicable to future deep-space flight applications. In all cases the experimental results will be compared to preflight predictions, based upon analyses of the links.

A. Flight Opportunities

One of the significant uncertainties in our preflight knowledge of the X-band uplink flight performance is an incomplete understanding of the complex effects of the propagation medium, especially the tropospheric phase scintillations due to

water vapor variations, and fluctuations of signal amplitude and phase due to charged particles in the ionosphere, solar corona and solar wind. The tropospheric phase error may be a limiting factor in some future radiometric applications, such as gravitational wave searches. The charged particle effects are very important to near-sun communications, such as will be encountered by the projected Starprobe mission. The charged particle effects are also important to ultrastable doppler tracking in the antisolar direction for the possible future gravitational wave searches. Current understanding is that such detection experiments are only feasible at oppositions (i.e., viewing the spacecraft in the antisolar direction) with significant earth-spacecraft distances.

It is therefore important to test the X-band uplink in as many of the diverse propagation environments as possible. Fortunately, the ISPM trajectory provides flight opportunities which will enable separation of the dominant propagation effects. The propagation conditions range from nighttime spacecraft viewing with minimum solar plasma and ionospheric effects to the superior conjunction conditions when the sun is between the earth and spacecraft, less than 2 degrees off the line-of-sight propagation path.

It is also desirable to check out and calibrate the instrumentation stability of the end-to-end system early in the mission under strong signal conditions with minimal media effects, and to compare the performance again later at far distance under similar media conditions. These requirements suggest close-in and long-range X-band uplink sequences near solar oppositions. The long-range opposition gives the opportunity to obtain two types of data. First, it will show the advantages of X-X coherent telemetry vs S-X under weak signal, but "quiet" environmental conditions. Secondly, the quiet environment is precisely the one that gives an insight into the feasibility of gravitational wave search experiments by measuring the actual plasma noise floor in the antisolar direction using X-band uplink. The plasma noise floor will be one of ultimate limits (along with unmodelled tropospheric errors) until simultaneous uplinks are available for calibrating the plasma component.

Figure 5 shows two aspects of the ISPM trajectory, the range and the sun-earth-probe angle. Together, these plots illustrate the unique characteristics of the ISPM trajectory; viz., the two spacecraft (only one shown here) proceed out to Jupiter in the plane of the ecliptic, where they are deflected by Jupiter gravity up out of the ecliptic plane, and then fall back over the poles of the sun. While the out-of-ecliptic phase is prime for ISPM science, it is the outward bound part of the trajectory in the ecliptic plane that offers the X-band uplink all of the conditions needed to perform a good survey of X-band uplink capabilities.

B. Data Acquisition Phases

The principal data acquisition phases providing for accomplishment of the demonstration objectives within the ISPM trajectory constraints are indicated in Fig. 5. The three experiment phases are (1) the system calibrations at the first opposition, (2) superior conjunction demonstration, and (3) long-range demonstration around the second opposition. As described in Table 1, each phase utilizes its unique propagation conditions for acquisition of different data types.

Each data acquisition phase consists of 30 to 40 spacecraft passes, a few of which are "fully dedicated" to the X-band uplink demonstration, while the rest may be performed concurrently with other ISPM data acquisition activities. The term "fully dedicated pass" means one in which not only the telecom system would be configured to accommodate the X-band uplink experiment but also the events and modes of the spacecraft would be maintained in a "quiet" or unchanging condition — both thermally and dynamically. Fully dedicated passes are required only for selected doppler stability measurements to establish the phase stability threshold.

IV. Expected Improvement in Telecommunications Performance

The improvement in telecommunications functions expected from an X-band (approximately 7.2 GHz) vs S-band uplink (2.1 GHz) is due to two well-known advantages of high radio frequencies.

First, antenna gain is proportional to the square of frequency. The space loss, on the other hand, is also proportional to the square of frequency. Since two antennas are involved in a communications link, the net effect of a higher frequency will be a gain by a factor of approximately the square of the frequency ratio.² Thus the power received at the spacecraft increases by about 10.6 dB for the same ground transmitter power and given dimensions and efficiencies of the ground and spacecraft antennas. This advantage, in reverse, has been exploited by Voyager using X-band *downlinks* to increase telemetry rates substantially over previous S-band capabilities.

Secondly, X-band transmissions are much less affected by phase fluctuations induced by charged particles, locally in the ionosphere, and in the tenuous, but extended, solar corona or solar wind of interplanetary space. A small disadvantage is that X-band is more sensitive to weather effects than S-band.

² Stated in another way: the effective isotropically radiated power (EIRP) transmitted to the spacecraft increases by $(f_x/f_s)^2$.

A. Doppler Stability Improvement

It is phase fluctuations due to charged particles that have become the limiting factor in discerning at S-band the minute doppler signatures below the 10^{-14} level such as might be encountered in gravitational-wave searches of the future. Ultimately, a simultaneous dual-frequency uplink and simultaneous dual-frequency downlink will permit a much better calibration of the charged-particle contribution to the doppler error budget. Meantime, the X-band uplink, used with a dual-frequency downlink on ISPM, should reduce the error considerably. Figure 6 shows the expected improvement, first with X-band uplink on ISPM and, in the future, with a simultaneous dual-frequency uplink. The error budget of the next generation also anticipates advances in calibrating the wet troposphere fluctuations plus further improvements in the stabilities of timing reference and distribution systems.

The ISPM experiment will include as many of these link calibrations as practicable. A prime example is the planned use of a water vapor radiometer at DSS 13 for monitoring the tropospheric scintillations during X-band uplink experiment passes.

B. Command Enhancement

Command enhancement at X-band derives from both the gain in EIRP and the reduction in phase fluctuations due to charged particles. The experiment will test this capability at low sun-earth-probe (SEP) angles. It is expected that reliable commanding should be possible down to an SEP angle of 2 degrees, with bit error rates of less than 10^{-5} . This would reduce the command "blackout" zone now encountered with S-band uplink communications at solar conjunctions.

C. Two-Way Coherent Telemetry Data-Rate Improvement

A demonstration of improved two-way coherent telemetry performance will be conducted under weak signal, but quiet environmental conditions selected to present unambiguously the advantage of using X-X vs S-X two-way coherent telemetry. These conditions are best met at the time of second opposition around September 1986, when both the spacecraft range and the SEP angle are large, approximately 4 AU and 177 degrees, respectively.

The telemetry performance improvement of an X-X link over an S-X link is realized from a reduction in radio loss, the term applied to the performance degradation in the received data due to imperfect tracking of the downlink carrier phase. It can be shown that the downlink carrier phase jitter in a two-way coherent link consists not only of the downlink jitter due to the ground receiver thermal noise and media-induced

signal fluctuations but also of all the noise accumulated on the uplink, multiplied by the turnaround frequency ratio of the transponder. Obviously, the X-X link gives an advantage in turnaround ratio (880/749 vs 880/221) over the S-X, plus an increase in uplink EIRP of approximately 10 dB.

The net improvement in data rate capability for convolutionally coded telemetry is approximately 3 dB for the long-range, weak-signal conditions that will exist at the mission time selected for these tests. In effect, the two-way X-X telemetry radio loss should approach that of a one-way telemetry link using the auxiliary oscillator as the downlink carrier reference.

D. Ranging Improvement

The ranging signal-to-noise ratio (SNR) as received at the DSN is determined by both the uplink and downlink parameters. Therefore, an X-X ranging link will demonstrate an improved SNR over its S-X counterpart as a direct beneficiary of the increased EIRP on the uplink. Added to this will be a somewhat smaller ranging radio loss for the same reasons that apply to two-way coherent telemetry.

Another approximately order-of-magnitude improvement in ranging accuracy should be realized by the reduction of errors caused by charged particles in the uplink path. The net improvement due to the X-band uplink will permit shorter integration times and therefore more data points with the same accuracy as that obtained with an S-band uplink.

V. Conceptual Operations Plan

ISPM is planning to operate throughout the mission in a "cruise mode," utilizing an 8-hour shift per day for each spacecraft, 5 days a week. The NASA MOS team will prepare for uplinking once a week the sequences necessary to program daily operations of the NASA spacecraft, including an 8-hour pass over an appropriate 34-meter station. It is important that the X-band uplink operations at DSS 13 do not seriously impact this routine.

The strategy presently planned for operations during the X-band uplink activity periods is to make the X-band uplink

experiment "nearly transparent" to the baseline operations of ISPM. This would be accomplished by incorporating into the sequences additional stored commands to configure the telecommunications system for *two* passes per day, one configuration to accommodate X-band uplink operations, using DSS 13, followed by a reconfiguration to execute normal ISPM operations at either DSS 42 or DSS 61. ISPM science data would continue to be recorded during the DSS 13 tracking. Thus, no ISPM data would be forfeited nor would 34-meter station activities be altered.

Let us consider a particular example, in this case a day's activities consisting of an X-band uplink doppler stability measurement conducted at DSS 13 followed by a routine ISPM data dump to DSS 42. The event sequences for these activities would have commenced just after the previous day's ISPM pass, at which time the spacecraft would have been configured for the upcoming X-band uplink from DSS 13. This mode would call for turn-on of the X- to S-band downconverter and for setting the telemetry modulation index at zero to maximize the downlink carrier power. These stored commands would have been executed sufficiently ahead of the DSS 13 pass to allow the spacecraft to come to thermal and dynamic equilibrium. Following the DSS 13 track, the telecommunications system would be reconfigured, again by stored command, to turn off the downconverter and reset the telemetry modulation index to execute the ISPM daily tape recorder playback to DSS 42. At the conclusion of that pass the spacecraft configuration would immediately be placed in the X-band uplink mode required for the next day. This dual-pass routine would be followed through the X-band uplink activity period.

There are several areas where further coordination with the ISPM Mission Operations System is necessary. The key MOS functions affected by the X-band uplink experiment are summarized in Table 2. The X-band uplink requirements and impacts will be worked as a continuing effort with the ISPM Mission Operations Design Team. Sequences accommodating the X-band uplink will be designed and tested before launch, as is the plan for all the NASA spacecraft sequences. Each sequence format will have sufficient flexibility to accept parametric changes during the mission.

References

1. Miller, R. B., "International Solar Polar Mission," *TDA Progress Report 42-59*, Jet Propulsion Laboratory, Pasadena, Calif., October 15, 1980.
2. Berman, A. L., "The Gravitational Wave Detection Experiment: Description and Anticipated Requirements," *DSN Progress Report 42-46*, Jet Propulsion Laboratory, Pasadena, Calif., August 15, 1978.
3. Kolbly, R. B., "20 kW X-Band Uplink Transmitter Development," *TDA Progress Report 42-60*, Jet Propulsion Laboratory, Pasadena, Calif., December 15, 1980.
4. Hartop, R., Johns, C., and Kolbly, R., "X-Band Uplink Ground System Development," *DSN Progress Report 42-56*, Jet Propulsion Laboratory, Pasadena, Calif., April 15, 1980.
5. Kuhnle, P. F., "Hydrogen Maser Implementation in the Deep Space Network at the Jet Propulsion Laboratory," Proceedings of the 11th Annual PTTI Meeting, NASA Conf. Publication 2129, GSFC, Greenbelt, Md., 1979.
6. Williams, W., and Reilly, H., "A Prototype DSN X/S-Band Feed: DSS 13 Application Status, (Fourth Report), *TDA Progress Report 42-60*, Jet Propulsion Laboratory, Pasadena, Calif., December 15, 1980.

Table 1. ISPM X-band uplink technology demonstration — flight experiment phases

Experiment phase	Date ^a	Demonstration duration	Data required
Calibration at first opposition	July 1985	40 Passes (5 fully dedicated)	Carrier acquisition and tracking, ranging and two-way coherent telemetry vs uplink power level Doppler stability, X-U/L vs S-U/L (strong-signal conditions, minimal solar wind environment, minimal ionosphere and troposphere effect)
Superior conjunction demonstration	Feb. 1986	30 Passes (5 fully dedicated)	Command demonstration, X-U/L vs S-U/L Ranging demonstration and doppler, X-X and S vs S-X and S System noise temp vs SEP angle (disturbed solar plasma environment)
Long-range demonstration	Around Sept. 1986	40 Passes (5 fully dedicated)	Two-way coherent telemetry, X-U/L vs S-U/L Doppler demonstration X-X and S vs S-X and S (far range, quiet spacecraft, quiet natural environment)

^aBased on tandem-launch trajectory data for March 29, 1985 launch.

Table 2. Effects of X-band uplink on ISPM daily operations

MOS function	Projected impact
DSN scheduling	Two-station per day coverage is implied during X-band uplink activity periods: DSS 13 for X-band uplink sequences, DSS 42 or DSS 61 for routine command, navigation and telemetry.
Stored command loads	Approximately 10 additional stored commands
Telemetry data rates	Downlink path losses are increased if X-diplexer is left in circuit during normal ISPM telemetry return. Option exists to switch X-diplexer IN/OUT for X-band uplink or telemetry, respectively. Desirability of this option is under study
Engineering data records	X-band uplink will require engineering records of spacecraft functions occurring during many X-band uplink passes. ISPM Ground Data System is required to provide such data within 24 hours (tapes and hard copy).

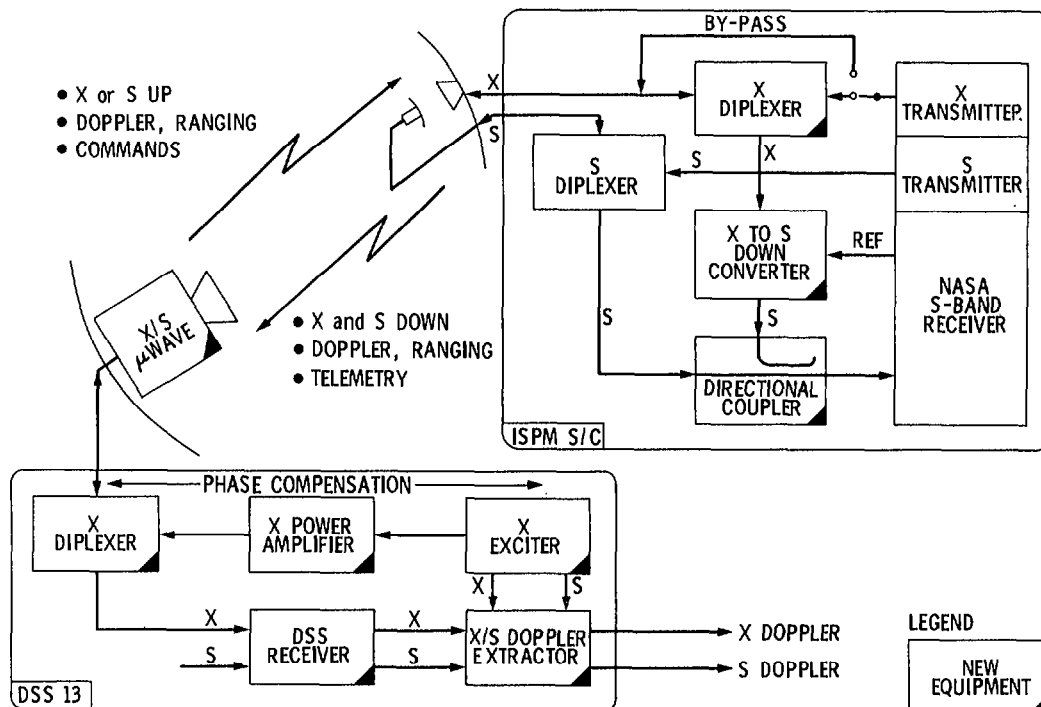


Fig. 1. Block diagram of the ISPM X-band uplink demonstration telecommunication system

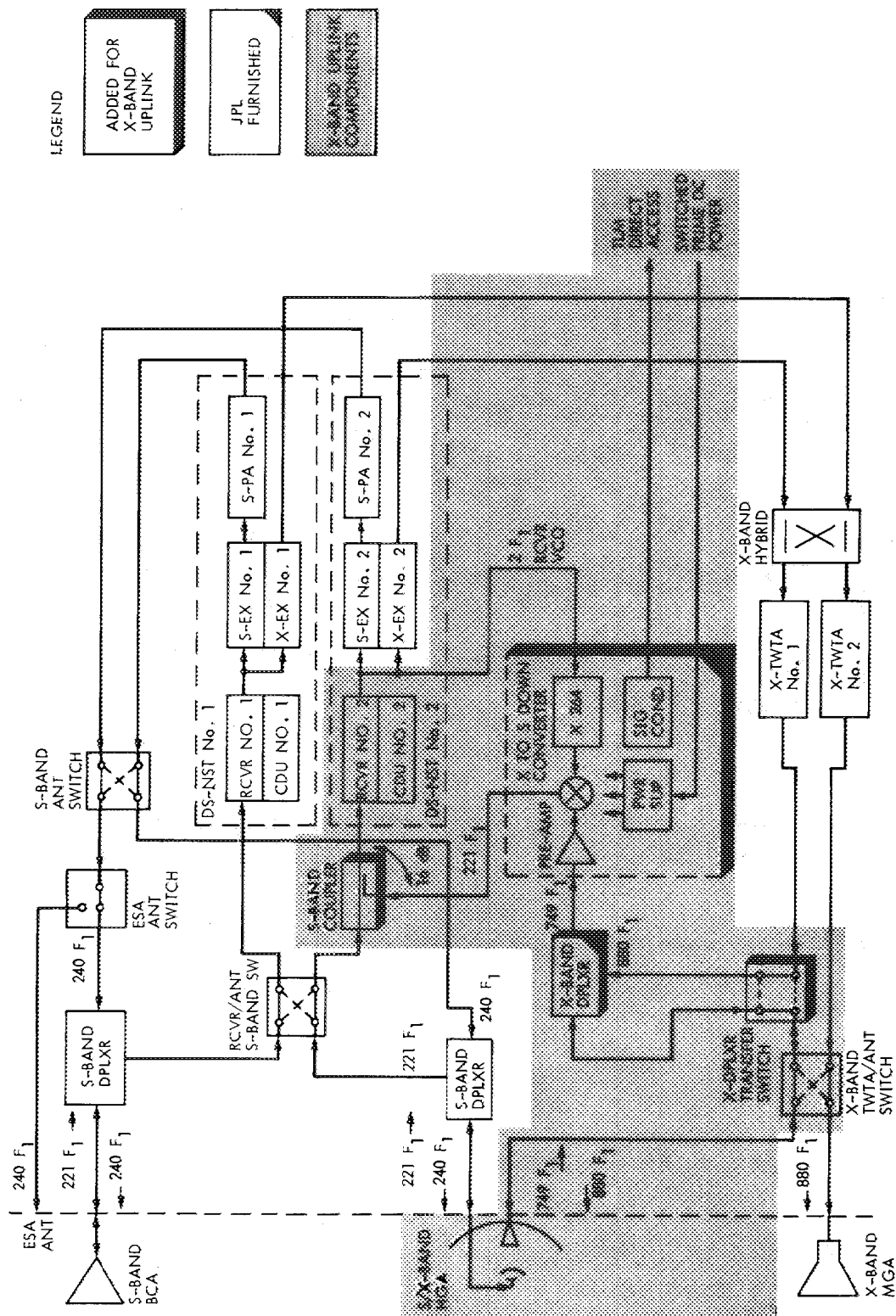


Fig. 2. ISPM spacecraft modifications for X-band uplink

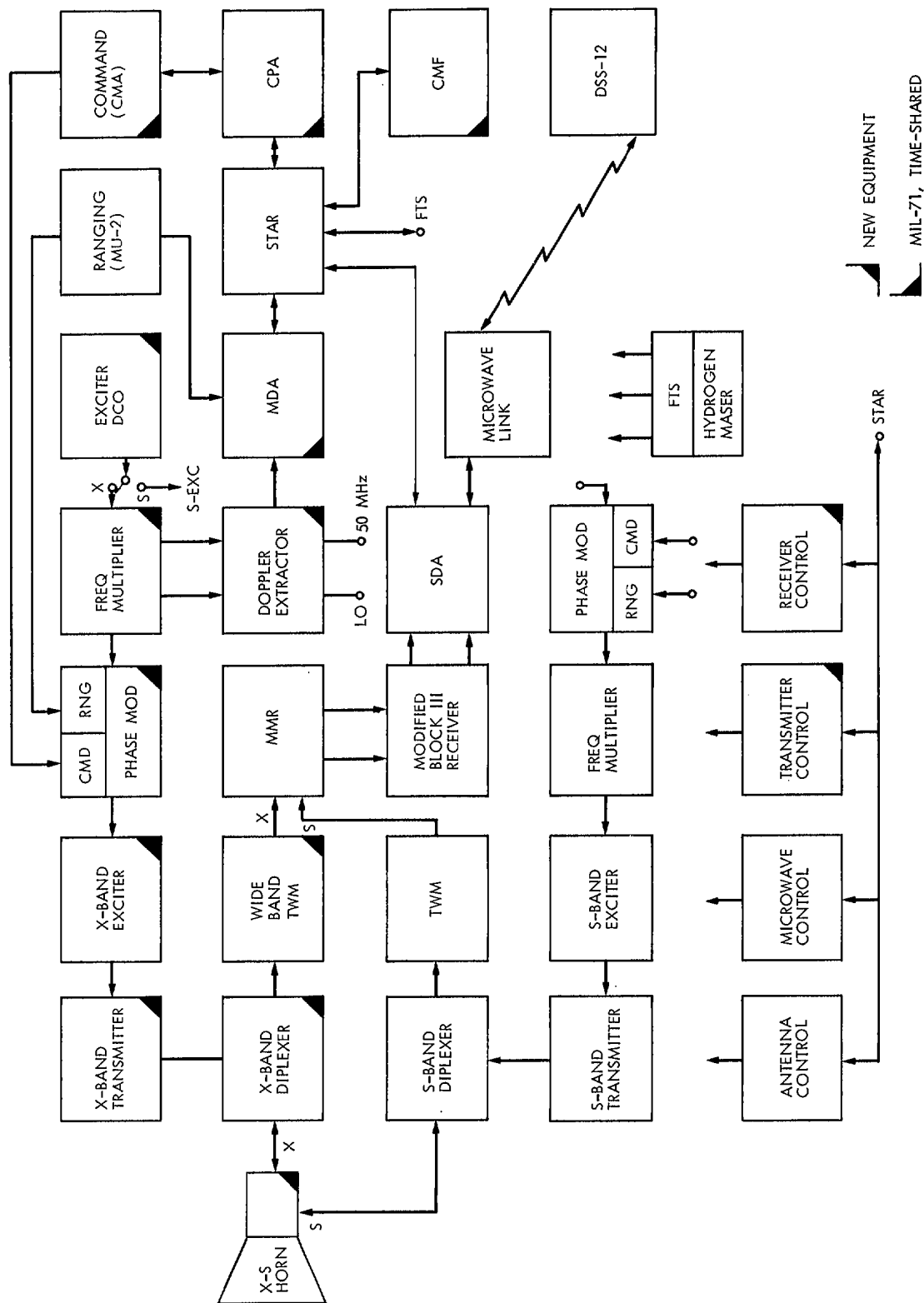


Fig. 3. Block diagram of DSS 13 X-band uplink elements

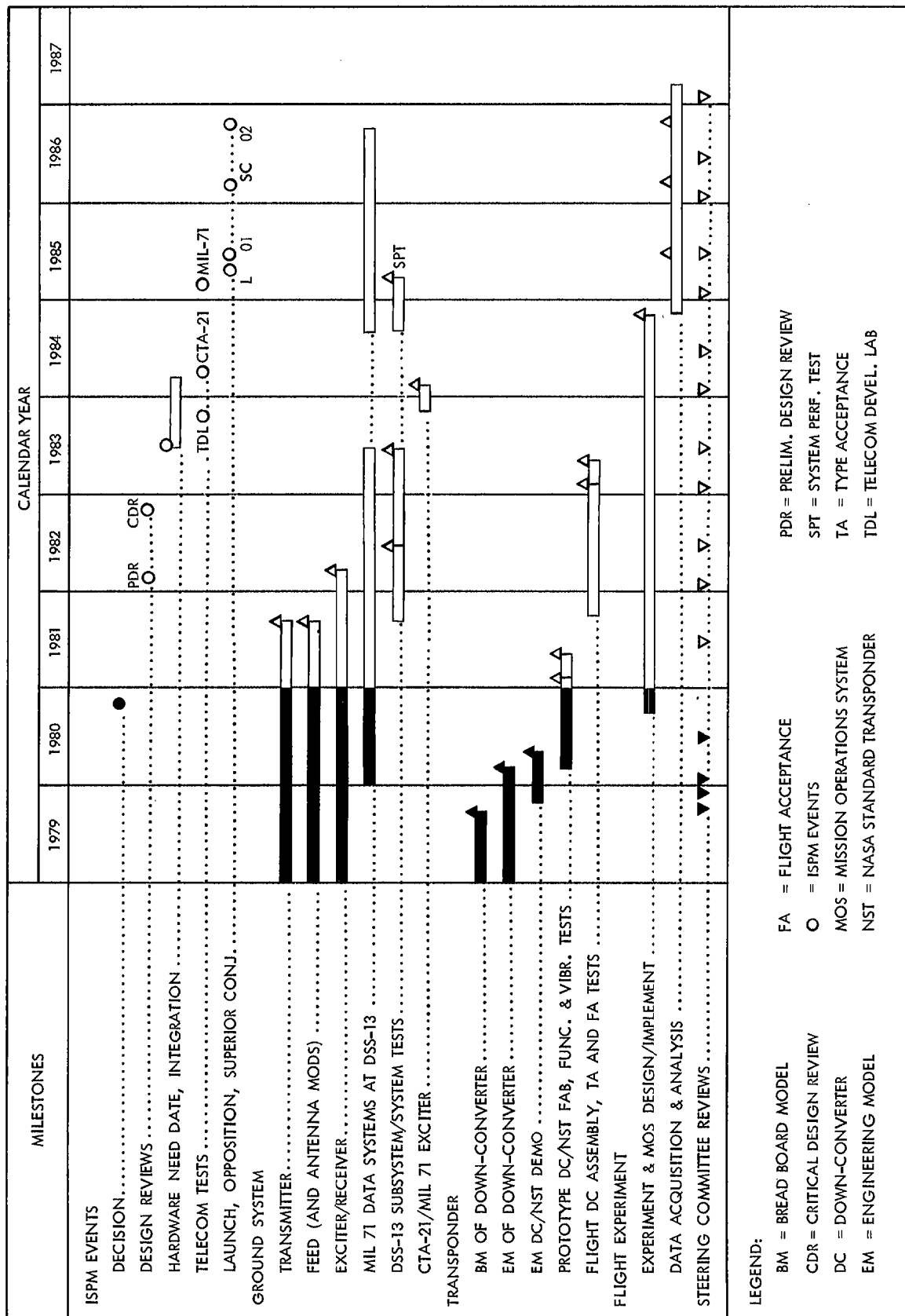


Fig. 4. ISPM X-band uplink demonstration schedule

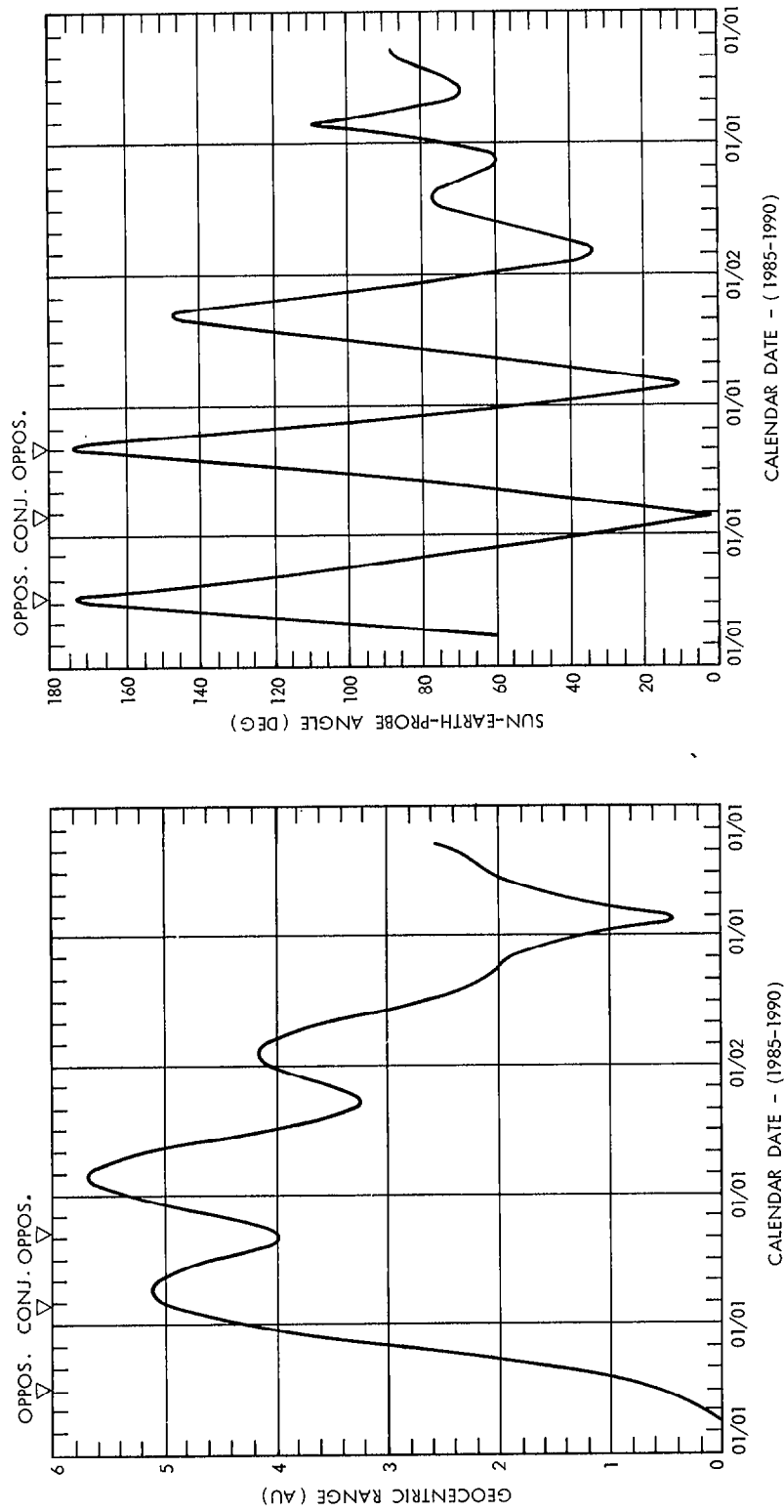


Fig. 5. Typical ISPM geocentric range and sun-earth-probe angle (3/29/85 launch)

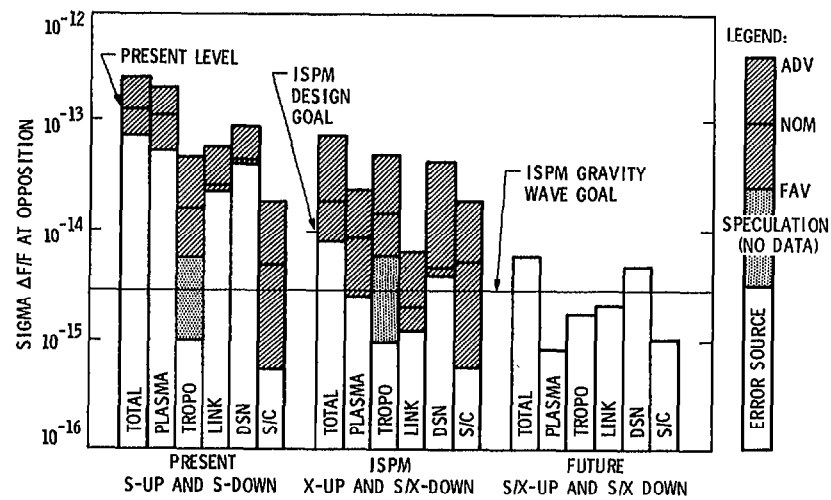


Fig. 6. Doppler error reduction with X-band uplink at solar opposition with 1000 second sampling